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Quantitative Risk Assessment on a Hydrogen Refuelling Station

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The Directive 2014/94/UE (DAFI, Alternative Fuel Initiative Directive) on the deployment of alternative fuels (i.e. hydrogen) infrastructures has been recently transposed into national law in Italy. Consequently, the technical regulation on fire prevention for H_2 fuelling stations has been updated, in order to consider the current maximum delivery pressure (700 bar) of gaseous hydrogen for road vehicles. This technical regulation establishes the prescriptive safety distance from a piece of equipment. In the case of a new station, an assessment of the frequency of the event and its potential consequences is necessary. This is to understand which risk can reasonably be mitigated by a safety distance or whether additional mitigation or prevention measures should be taken. This paper presents the quantitative risk assessment (QRA) study on a hydrogen station planned to be installed, study which aims at determining the safety distances. Such study utilizes the Sandia-developed QRA tool, Hydrogen Risk Analysis Model (HyRAM), to calculate risk values when developing risk-equivalent plans. HyRAM combines reduced order deterministic models that characterize hydrogen release and flame behavior with probabilistic risk models to quantify risk values. Thanks to HyRAM tool it is possible to estimate physical effects and consequences on people and structures and plants, related to risk scenarios, by means of a damage model library. Use of risk assessment may allow station owners and designers to flexibly define station-specific mitigations, with the purpose of achieving equal or better levels of safety with respect to prescriptive recommendation levels, as suggested by ISO19880-1 (2018).

1. Introduction

Hydrogen-powered motor vehicles have at present very low market penetration rates. For this reason a build-up of a sufficient hydrogen refuelling infrastructure is essential to make larger-scale deployment of hydrogen-powered motor vehicle possible. The Directive 2014/94/EU (DAFI, Alternative Fuel Initiative Directive), transposed into law in Italy with the Legislative Decree 257 on December 16, 2016, establishes a common framework of measures for the deployment of alternative fuels infrastructures in the European Union in order to minimize dependence on oil and to mitigate the environmental impact of transport. This Directive sets out minimum requirements for the building-up of an alternative fuels infrastructure, including refuelling points for hydrogen, to be implemented by means of Member States' national policy frameworks. In Italy, the technical regulation on fire prevention for H_2 refuelling station (DM August 31, 2006) establishes a maximum pressure of 350 bar of gaseous hydrogen, which is not consistent with the delivery pressure of new-generation hydrogen vehicles (up to 700 bar), which is needed to ensure greater quantity of stored gaseous hydrogen and less refill time. The authors worked together to break down this obsolescence constraint by revisiting and modifying the current technical regulation to guarantee adequate pressure to the new technological standards.
In this general framework there is a fundamental issue concerning the safety of people, which is generally accomplished by specifying prescriptive separation distances. A safety distance is defined as the minimum separation between a hazard source and an object (human, equipment or environment) that mitigates the effect of a likely foreseeable incident and prevents a minor incident from escalating to a larger one (HyApproval, 2008; EIGA, 2007). Among the various methods and tools for determining safety distances, the

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risk-informed method combines elements from a quantitative risk analysis and data obtained from a deterministic approach. The general QRA framework for hydrogen uses a combination of probabilistic and physical models, with the aim of assessing the likelihood and impacts of various hydrogen release and ignition scenarios, which can lead to thermal and overpressure hazards. The primary scenario develops from the release and subsequent ignition of hydrogen. The two main hazards are: exposure to thermal effects from jet fires and deflagrations; and exposure to overpressures from deflagrations and detonations. Both of these hazards can affect people, property, structures, and the environment directly or indirectly. Several models with data linkages are typically needed to characterize the physical effects of the hazards. Information from the physical effect models is then passed into probit functions used to calculate consequences in terms of harm or loss.QRA allows to identify and quantify the various scenarios for an uncontrolled release of hydrogen and then to establish the contribution of these scenarios to the risk, taking also into account application of prevention and mitigation measures. For the assessment of the safety distances, the risk-informed method then imposes the selection of a risk level. While general QRA methods are applicable to hydrogen systems in industrial plant, more widespread use of QRA for refuelling stations was previously limited due to gaps in available data and models relevant to these hydrogen applications. However, research progress in models, data and tools is actively addressing many of these gaps. This paper describes an application of the QRA method to a hydrogen station planned to be installed. Hydrogen Risk Analysis Model software was the analysis. It provides a standard methodology for quantitative risk analysis by assessing safety within a hydrogen supply and storage infrastructure. In this analysis higher gas storage and delivery pressures than those defined by the technical regulation (DM August 31, 2006) were considered for the hydrogen refuelling station, along with the assesmnet of the required separation distances.

2. Software HyRAM

The analysis was carried out using HyRAM software, developed by SNL (Sandia National Laboratories) for the FCTO (Fuel Cell Technologies Office) of DOE (U.S. Department of Energy). HyRAM employes both probabilistic and deterministic models for the identification and quantification of incidental scenarios. It also allows to predict the physical effects associated with them and the consequences that such incidents could generate both on people and on structures, through the use of various damage models (Groth et al., 2016). HyRAM uses various calculation models (Groth et al., 2015) to describe the behavior of hydrogen (thermodynamic state equation), the consequences of the release of hydrogen, the concentration profile of a jet (without ignition), the temperature profile, lenght and the heat flow generated by a jet fire, risk assessment and management. In particular, the flame and trajectory results are based on the Notional Nozzle Model developed by Birch et al. (1987). Assuming flow adiabatic reversible (isoentropic) from the equations of conservation of mass and momentum Birch et al. (1984) obtained the actual diameter of the jet after expansion is given by:

$$d_{eff} = d_2\sqrt{\frac{\rho_2 u_2 C_D}{\rho_3 u_3}} \qquad (1)$$

where d is the diameter, ρ the density and u the velocity of the gas while the subscript 2 indicates the jet outlet conditions and 3 the exit conditions after expansion through the notional nozzle. Birch models consider the temperature after expansion equal to the storage temperature, and the speed after expansion sonic. A successive development (Birch et al., 1987) of this model considered that the jet speed is calculated by equation:

$$u_3 = u_2 C_D - \frac{(P_3 - P_2)}{\rho_2 u_2 C_D} \qquad (2)$$

In HyRAM, the radial heat flux (in both directions perpendicular and parallel to the flame axis) is calculated through the Houf and Schefer (2007) flame radiation model, while to take account the buoyancy effects multiple source model is used (Hankinson and Lowersmith, 2012). This model considers that the total heat flux is given by point sources located on the flame axis, as follows:

$$q = \tau S_{rad}\frac{V_F}{A_f} \qquad (3)$$

where τ is the atmospheric transmissivity, S_{rad} is the total emitted radiative power, V_F is the view factor and A_f is the flame area.Once the heat flux is calculated in relation to the position and type of target, the damage is assessed. The damage assessment is done through the Probit function (Y), enable to estimate the number of expected deaths according to the thermal flow and the exposure time. Among Probit models included in HyRAM, Tsao and Perry (1979) model was used:

$$Y = -36.38 + 2.56 \times \ln(V) \quad (4)$$

where V is the thermal dose unit which combines the heat flux intensity and exposure time:

$$V = I^{4/3}\, t \quad (5)$$

3. Case study

The case study analysed refers to a pilot plant, planned to be installed, for the distribution of hydrogen for fuel cell vehicles. A refueling station 50m x 20 m has been hypothesized, operating 300 days per year, and where 50 vehicles per day are refuelled once a day, for a total of 15000 refuels per year. The plant is constituted by a compression, a storage and a distribution unit as showed in Figure 1. A multistage compressor is used and located in an outdoor area. Cylinder racks located outdoors are adopted as storage system. The geometrical characteristics and the operating conditions of the units are reported in Table 1.

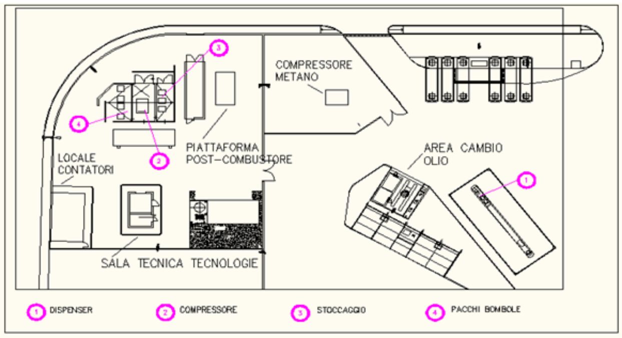


Figure 1: Layout of hydrogen refueling station

Table 1: Geometric characteristics and operating conditions of dispenser, compressor and storage units

	Dispenser	Compressor	Storage
Valves	7	11	9.52 mm
Instruments	4	6	9.52 mm
Joints	45	45	9.52 mm
Filters	2	2	9.52 mm
Hoses	4		9.52 mm
Compressors		1	
Pipe diameter (mm)	9.52	9.52	9.52
Pipe length (m)	20	20	10
H_2 Temperature (°C)	15	15	15
H_2 Pressure (bar)	350	600	480

3.1 Release frequencies and scenarios

Events considered were identified by a HazOP analysis. These events are related to the release of gaseous hydrogen (GH_2) from the dispenser area, compressor and high pressure storage unit. The possible scenarios that could occur after a hydrogen release are: unignited release, jet fire, explosion. The frequency of a scenario is determined once the frequency of the initiating event, which is the release of gaseous hydrogen, is evaluated. HyRAM contains default data for leak frequencies for hydrogen components. The probabilities were developed from a Bayesian process using generic leak probabilities and available hydrogen data (LaChance et al., 2009). Leak frequencies of the hydrogen components are expressed as a function of leak size which is defined as percentage of pipe diameter (0.01%, 0.1%, 1%, 10%, 100%). The frequency of scenarios was estimated through the event tree analysis (Norani et al., 2017). The most severe accident scenarios following release of GH2 are the jet fire (immediate ignition) and explosion (delayed ignition). According to HYSAFE program (Rodsaetre and Holmefjord, 2007) and Tchouvelev et al. (2006) the ignition probabilities are considered as a function of the GH_2 release rate (Table 2). For the fire scenario only a single fire source is assumed, multiple fire events are not considered, as well as multiple release scenarios and combination of multiple vents (domino effects) are not considered.

Table 2: Default ignition probabilities in HyRAM

Hydrogen release rate (kg/s)	Immediate ignition probability	Delayed ignition probability
<0.125	0.008	0.004
0.125-6.25	0.063	0.027
>6.25	0.23	0.12

3.2 AIR - Average Individual Risk

The risk for each scenario is obtained by the product of the frequency (f_i) of that scenario and the consequences (c_i) (in terms of fatality) caused by that scenario. HyRAM calculates the frequency of each scenario for each of the five leak sizes (0.01%, 0.1%, 1%, 10%, 100% of the pipe diameter) as the product of the frequency of a leak and the probabilities of each of the events leading to each end state. Then HyRAM samples a position for each exposed person and calculates the probability of fatality from the physical consequence at each position by using the probit models. The total number of fatalities is the sum of the product of the fatality probabilities and the number of exposed persons. The total fatality risk from the station PLL (Potential Loss of Life) is then calculated as the sum of the risk over all scenarios:

$$PLL = \sum_i f_i c_i \tag{6}$$

The AIR (Average Individual Risk), which is the number of fatalities per exposed individual, is calculated by dividing the total fatality risk from the station (PLL) by the total exposed population. In the following it was considered that the station has one attendant on site at a given time. From AIR calculation it is obtained a measure of the risk from the station to each individual.
For the evaluation of safety distances through the risk-informed method, it is necessary to choose a risk level. It was assumed an individual risk of 1×10^{-5} fatalities per year, value lower (about 1/3) than that the one adopted by EIGA (2007).

3.3 Input parameters of risk analysis

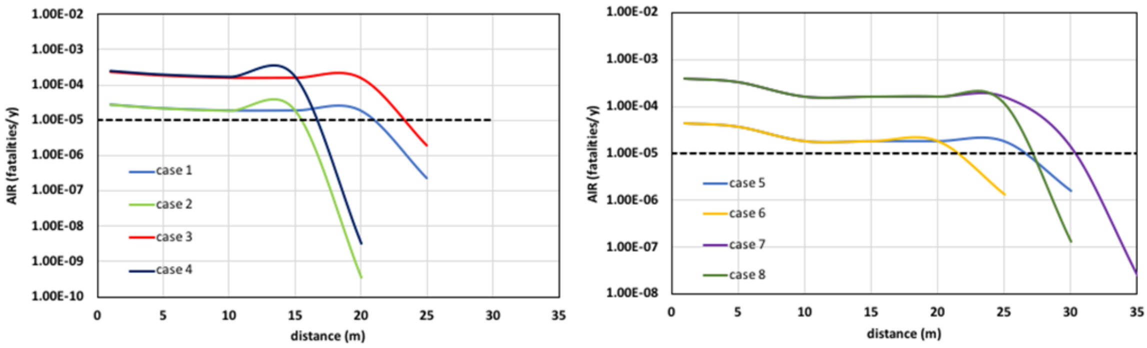
For the case study analysed, only jet fire scenarios were considered, because compressor is located outdoor and because an explosion scenario is not credible for the storage unit since the presence of pressure relief devices and leak-before-burst design specification of the sysytem. Furthermore, the presence of barriers between the hazard source and the target was not considered, while it is assumed the presence of a safety system that detect GH2 release and shut down the valves.
The target (the attendant of the station) was assumed to be positioned along the axis of the jet. Exposure times were assumed equal to 5 and 60 s for the dispenser, while 5 and 30 s for the compressor and storage unit. These times refer to the times of intervention of the safety systems, according to the Hyapproval project (Wurster, 2006). The input parameters for the analysis are reported in Table 3.

Table 3: Input parameters of risk analysis

Case	Unit	Pressure (bar)	Diameter (mm)	Probability leak detection	Exposure Time (s)
1	Dispenser	350	9.52	90%	60
2	Dispenser	350	9.52	90%	5
3	Dispenser	350	9.52	10%	60
4	Dispenser	350	9.52	10%	5
5	Compressor	600	9.52	90%	60
6	Compressor	600	9.52	90%	30
7	Compressor	600	9.52	10%	60
8	Compressor	600	9.52	10%	30
9	Storage	480	9.52	90%	60
10	Storage	480	9.52	90%	30
11	Storage	480	9.52	10%	60
12	Storage	480	9.52	10%	30

4. Results and discussion

This section presents results of calculation of safety distances for dispenser, compressor and storage units. An iterative procedure was performed until the target at a certain distance results to have an AIR value equals to 1×10^{-5} fatalities y^{-1}. For the dispenser, the results show that the most severe scenario, corresponding to a leak size equal to 100% of pipe diamter, has a higher frequency than those related to other leak size; this is due to the higher probability of ignition, which is a function of the release rate, although the lower leak frequency of the system components for 100% leak size scenario. Results for dispenser (case 1, 2, 3, 4) in terms of the AIR as a function of the distance are reported in Figure 2a, while those for compressor unit are reported in Figure 2b. For storage unit, the AIR calculated for case 9 and 10 is always less than 1 x 10^{-5} fatalities y^{-1}, because the frequency of scenarios is very low. The results in terms of safety distances are reported in Table 4.



a) b)

Figure 2: Comparison of the results for dispenser (a) and compressor (b)

Table 4: Safety distances for hazard units of refuelling station

Dispenser	Safety distance (m)	Compressor	Safety distance (m)	Storage unit	Safety distance (m)
Case 1	21.8	Case 5	27.5	Case 9	-
Case 2	17	Case 6	22.5	Case 10	-
Case 3	24	Case 7	30	Case 11	7
Case 4	18.6	Case 8	28.5	Case 12	6

From Table 4 it can be observed that for the dispenser and the compressor the safety distances are reduced to 17 and 22.5 m (case 2 and case 6, respectively) when safety systems are affective and are activated in short time (shorter exposure time). These conditions can be achieved for the dispenser if it operates in conjunction with an emergency shutdown function, which may be automatically activated by the dispenser control system or manually activated. Activation of the emergency shutdown function shall cut off the flow of hydrogen gas to the dispenser and vehicle which initiated the shutdown by closing the automatic isolation valves. In the case of compressor both inlet and outlet pressure should be monitored by a pressure indicator/switch, with the control system instigating a shutdown of compressor. In the case of high pressure storage unit the safety systems assures values of AIR below the 1 x 10^{-5} fatalities y^{-1}.

Table 5: Comparison of safety distances for dispenser, compressor and storage unit at different pressures

	DISPENSER		COMPRESSOR		STORAGE UNIT	
Diameter (mm)	Safety distance (m)		Safety distance (m)		Safety distance(m)	
Pressure	350 bar	700 bar	600 bar	800 bar	480 bar	800 bar
6	9	12.5	14.1	15.8	-	-
9.52	17	23.8	22.5	27	-	-
11	21.4	28.5	32.1	38.2	-	-

In Table 5 are reported the safety distances evaluated at various pressures and pipe diameters. They refer to the case of 90% leak detection and exposure time of 5 s for dispenser and 30 s for compressor and storage unit. As expected, an increase of the operative pressure of the refuelling station, as required by the higher delivery pressure for the new-generation hydrogen vehicles, determines higher safety distances. At the dispenser an increase in delivery pressure from 350 to 700 bar corresponds to an increase of safety distance from 17 to 23.8 m (about 1.4 times). Correspondingly, the lower diameter pipe (6 mm vs 9.52 mm) can decrease the safety distance at values lower than 15 m. This value corresponds to the prescriptive distance established in the new-version of the Italian technical regulation on fire prevention for H_2 refuelling station. In the case of compressor a fire barrier may be used as a mitigation option to reduce safety distances. If a fire barrier is used as a mitigation option, it shall be made of non-combustible materials.

5. Conclusions

One major aim of risk assessment is to provide a description of the hazard scenarios, their causes and consequences and uncertainties, for use in decision making. This information can be used to make changes to the design and siting of a hydrogen refuelling station with the aim to reduce the risk posed to people, surrounding plants/buildings and the environment. This paper presents the quantitative risk assessment study on a hydrogen station planned to be installed in Italy. The safety distances were determined and the protection and mitigation measures to reduce the safety distances were identified.

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